Infrared Spectroscopy of V4334 Sgr (Sakurai's Object)

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Abstract.
IR spectroscopy and photometry in the 0.8 – 2.4 and 3 – 14 μm regions are reported for seven dates between 1998 March 21 and 2000 July 20. The shorter wavelength region displays a smooth continuum increasing to longer wavelengths that is indicative of the Wien tail of a Planck function. Only the HeI 1.0830 line is present early and it shows a P-Cygni profile which later disappears. The long wave spectra show a smooth continuum between 3 and 13 μm that was well fit by a gray body at 1000 K. A weak, unidentified emission feature appears between 8 and 10 μm.

1. Introduction

"Sakurai's Object" (V4334 Sgr) was discovered by Yukio Sakurai on Feb. 20.806 UT at 17 52 33 .5 −17 40 52 (J2000.0) (l^{II}= 10.4849 b^{II}= 4.4143) (Nakano, 1996). During its rise to maximum light (Benetti et al. 1996; Duerbeck et al. 1996), its slow rise time suggested that it was a cooling white dwarf whose helium shell ignited in a final thermal pulse (Iben et al. 1983, 1995, 1996). Only two other stars are known to be "final helium flash" stars, V605 Aql whose outburst and subsequent fading occurred during 1919-1923 (Wolf 1920), and FG Sge in 1894 (Gonzalez et al. 1998 and references therein).

Duerbeck et al. (1996) placed V4334 Sgr's outburst date at JD 2449620 (September 24.5, 1994). The object is surrounded by an old planetary nebula (Duerbeck and Benetti 1996; Kerber et al. 1999a,b; Pollacco 1999) which further suggests that the evolutionary state of the object is advanced. Based on AAVSO light curves (Kerber et al. 1999a), a significant dust formation event occurred on or about JD 2451015 (July 20.5 1998). Additional results and interpretation may

Table I. Observation Log

Date (UT)	JD*	Inst./Tele.	$\lambda\lambda$ (μm)	$\lambda/\Delta\lambda$	Aperture/slit ($''$)
1998 Mar 21.6	2450894	BASS/IRTF	3 – 13.5	~100	3.2 diam.
1998 Mar 22.6	2450895	BASS/IRTF	3 – 13.5	~100	3.2 diam.
1998 May 12.5	2450946	BASS/IRTF	3 – 13.5	~100	3.2 diam.
1998 Sep 30.1	2451087	NIRIS/Lick	0.8 – 2.5	600	1 width
1998 Oct 01.1	2451088	BASS/MLOF	3 – 13.5	~100	12.8 diam.
1999 Apr 29	2451298	2MASS/CTIO	JHK		
2000 Jul 20.2	2451746	NIRIS/Lick	0.8 – 2.5	600	2.7 width
		Related Dates			
1994 Sep 24.5	2449620	"outburst"		Duerbeck et al. 1999	
1998 Jul 12.5	2451014	strong dust formation event		(Kerber et al. 1999)	

* JD rounded to nearest whole day

be found in Tyne et al. (2000), Pavalenko et al. (2000) and Duerbeck et al. (2000).

The frontispiece shows the 2MASS image of the star and its surroundings taken 1999 April 29 at CTIO (Skrutskie et al. 1997: Cutri 2000). Its unusually red appearance is confirmed by its 2MASS J, H and K magnitudes of 11.5, 8.7 and 6.4 respectively. In this paper we report infrared (IR) spectroscopy of the object between 1998 March 21 and 2000 July 19.

2. Observations

The observations reported here are summarized in Table I. The short wavelength region was observed using the Lick 3 meter telescope and the Aerospace Near Infrared Imaging Spectrograph (Rudy et al. 1999). The spectrograph incorporates two separate channels, divided at 1.38 μm, to provide nearly continuous coverage between 0.8 and 2.5 μm. To facilitate background removal, spectra were acquired at 2 locations (separated by 20 arc secs) along the slit. Wavelength calibration was done by taking spectra of emission line lamps. The slit was oriented N/S and the nod distance was $20''$. In 1998 the standard star was HR 6269 (G3V), a solar-type star. In 2000 the standard was HR 6496 (F7V). Flux calibration was performed by taking the spectral shapes from Kurucz (1991) and setting the level based on standard stars (Elias 1982). For the 2000 NIRIS observations, the object could not

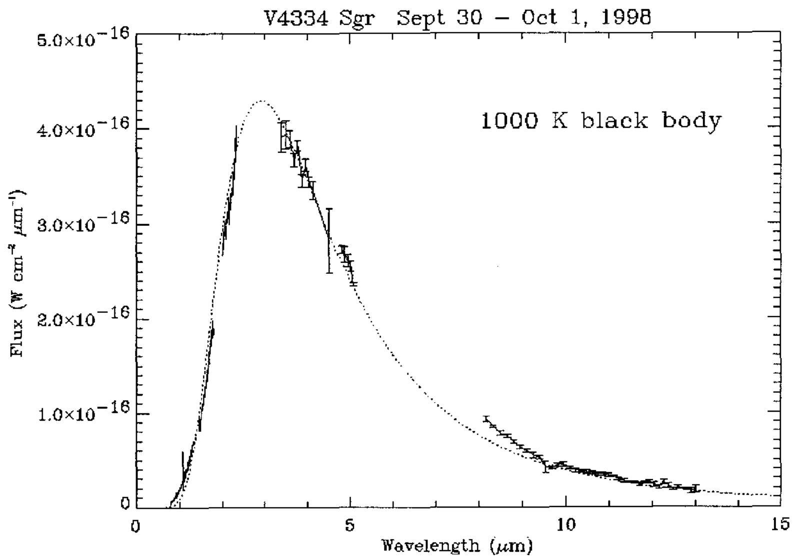

Figure 1. Spectrum of Sakurai's Object taken 1998 Sept 30 from Lick and the near simultaneous spectrum taken at Mt Lemmon on 1998 Oct 1. A 1000 K black body spectrum that has been scaled to fit the observations is overplotted (dashed). The spectrum matches the black body quite closely and this suggests that the dust shell is nearly isothermal. The spectrum also shows the He I line $\lambda 1.0830$ in emission and a weak continuum feature between 8 and 10 microns Notably absent are the silicate feature in the 10 μm region, the UIR/PAH bands at 3.3, 8.6 and 11.2 μm and the C-H band at 3.4 μm.

be detected in the visible and as a result, guiding errors rendered the photometry uncertain although the shape of the spectrum is reliable.

The 3–14 μm region was observed with the Aerospace Broadband Array Spectrograph System (BASS; Hackwell et al. 1990) using the NASA Infrared telescope Facility (IRTF) 3 meter or the Mount Lemmon Observing Facility (MLOF) 1.6 meter. The standard star used was α Lyr and it was assumed to be 0.0 magnitude at all wavelengths. The chop size and direction were 30$''$ and north-south.

3. Spectra

Figure 1 shows the spectrum taken 1998 Sept 30 from Lick and the near simultaneous spectrum taken at Mt Lemmon on 1998 Oct 1. Also shown is a 1000 K black body spectrum that has been scaled to fit the

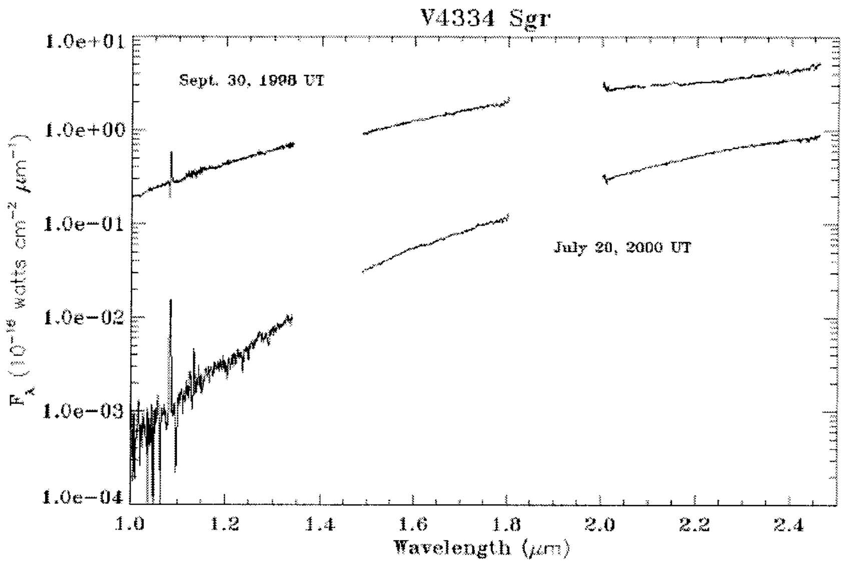

Figure 2. NIRIS spectra of V4334 Sgr on two dates separated by about two years. Both are featureless continuua except for the He I $\lambda 1.0830$ line showing a classic P-Cygni profile in 1998 but not in 2000. No HI lines were detected and the continuua were well fit by black body curves.

observations. The spectra match the black body quite closely and this suggests that the dust shell is nearly isothermal. Notably absent are the silicate feature in the 10 μm region, the UIR/PAH bands at 3.3, 8.6 and 11.2 μm and the C-H band at 3.4 μm. Given the C-rich nature of the object (Duerbeck and Benetti 1996) and the dust formation that took place soon after the outburst which obscured the central star, the spectra would seem to be thermal emission from an optically thick, carbonaceous, dust shell. Spectra obtained in May and March of 1998 show a very similar shape, though slightly warmer and fainter (see Table 2 and Section 4). There appears to be a weak emission feature between 8 and 9.5 μm. The feature is not an artifact of reduction because in all cases α Lyr was used as the standard and its flux model is featureless.

Figure 2 displays the 0.8 – 2.5 μm part of Figure 1 taken on 1998 Sept 30 (JD2451087) and also shown is the spectrum obtained on 2000 July 20.2 (JD2451746). Both spectra showed the He I line $\lambda 1.0830$ in emission and a closer look at the earlier spectrum reveals a classic P-Cygni profile (Figure 3). The separation between the blue absorption minimum and the red emission maximum is about 800 km s^{-1}. Owing to the low signal level and absence of continuum in the later spectrum, the presence of a P-Cygni profile is difficult to assess. No hydrogen

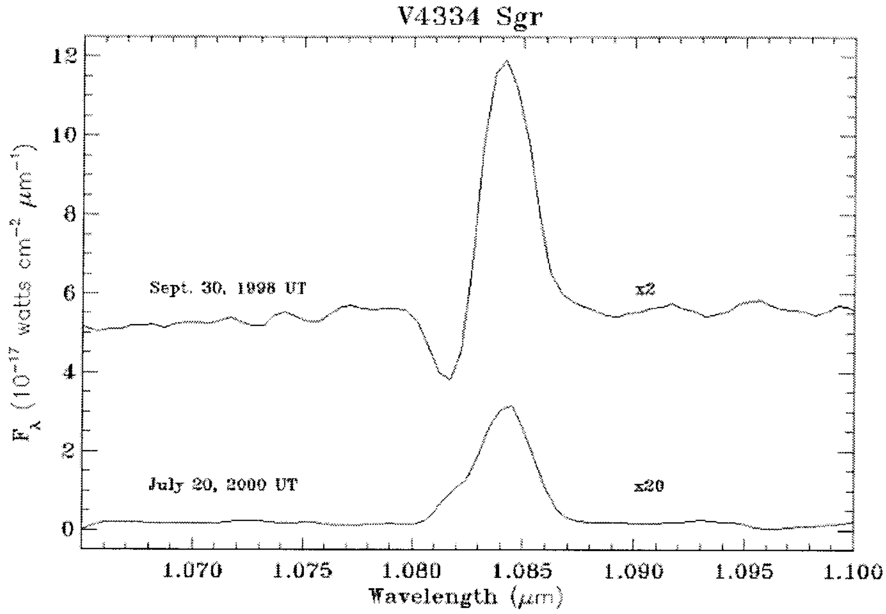

Figure 3. The He I line λ1.0830 in emission on 1998 Sept 30 showing a classic P-Cygni profile The separation between the blue absorption minimum and the red emission maximum is about 800 km s^{-1}. The later spectrum from 2000 July 20 shows only a hint of the P-Cygni profile.

lines were detected in any of our spectra, a result consistent with the object's advanced stage of evolution: virtually all of the hydrogen has been burned, or is so underabundant as to be undetectable or obscured by the dust shell. The continuua in the spectra appear to be the Wien tails of a blackbody. In 1998 the spectrum was near 1000 K but in 2000 the shell had cooled and is clearly cooler than about 500 K.

4. Photometry

In 1998 at L,M and N, the object was growing brighter and cooler (Table II). Only at L did the object first dim slightly before brightening again. The best fit temperatures in March, May and September of 1998 were 1170, 1030 and 960 K, respectively. At J,H and K however, the object grew dimmer with time. This is consistent with an object that is cooling and whose peak emission is shifting to longer wavelengths. These results confirm and extend earlier near IR photometry by Kamath & Ashok (1999) and Eyres et al. (1998,1999).

Table II. Photometry

JD	J 1.215	H 1.654	K 2.179	L 3.547	M 4.769	N′ 10.0
2450894				3.37	2.68	1.88
				0.05	0.06	0.08
2450895				3.37	2.64	1.87
				0.06	0.11	0.06
2450946				3.40	2.53	1.63
				0.07	0.06	0.14
2451087	9.70	7.22	5.11			
	0.03	0.03	0.03			
2451088				3.17	2.20	1.23
				0.05	0.11	0.07
2451298	11.51	8.70	6.37			
	0.025	0.032	0.012			
2451746	<14.4	<10.6	<7.6			

First line is magnitude, second line is 1 standard deviation. N′: 9.5 – 10.5 μm. JHK magnitudes on JD2451087 use slightly different photometric systems than on JD2451298 and 2451746. On JD 2451745 the object was invisible in the field so guiding uncertainties lead to photometric uncertainties. However, we believe that the relative brightnesses are reliable.

5. Discussion

The absence of a short wavelength stellar continuum turning upwards towards shorter wavelengths suggests one of three possibilities: The central star was (1) very cool and close enough to the temperature of the dust that its radiation is indistinguishable from the dust, (2) intrinsically very faint, or (3) being blocked by the dust. Having a central star the same temperature as the dust seems unlikely based on energetics. Furthermore, a star at 1000 K would display significant molecular absorptions and these were not observed. The remarkable Plankian nature of the emission – virtually unknown in any other astronomical object – suggests that the dust shell is optically thick. Its spectrum closely follows that of a black body and this is most easily explained in terms of a large optical depth, probably greater than 2–4 at K band. Such optical depths could well hide the central star powering the dust shell.

The feature between 8 and 10 μm, which also is present in the spectra obtained in 1998 March and May (not shown), is problematical. At first glance it is similar in shape and wavelength location to the SiO absorption feature seen in absorption in late type stars (Cohen et al. 1992), and therefore suggestive of an SiO emission feature. In view of the hydrogen-deficient nature of the object and its expected over-abundance of C,N,O, Si and Ne (Iben 1995), the object is believed to be C-rich and most of the oxygen would be in the form of CO with little left over to form SiO and silicates. On the other hand if SiO is present one might also expect SiO_4 dust like olivine, but none is seen. There is only one SiO resonance in the 0.8 – 14 μm region and so we were not able to search for confirming bands at other wavelengths. It is worth noting, however, that at different stages in its evolution, a star can be either O-rich or C-rich and such objects have been observed. The C-rich star IRAS 09425-6040 observed with ISO has both SiC and crystalline silicates in its spectrum. Molster et al. (1999) have also reported objects containing both C-rich and O-rich material. The feature could possibly be due to a cool dust component but we were unable to fit a separate black body curve to it without disrupting the otherwise excellent fit from the 1000k black body. As of this writing we have no explanation for this feature.

6. Summary and Conclusions

The IR spectrum of Sakurai's Object is remarkable for its close adherence to a single-temperature (1000 K) Planck function and for its lack of molecular emissions that would be expected from a star at this temperature. The most reasonable explanation is that we are seeing an optically-thick, perhaps carbonaceous, dust shell that is giving rise to most of the emission. The thin planetary nebula surrounding the dust shell from an earlier mass-loss event is probably producing the He I lines with P-Cygni profiles. Ho hydrogen emission was observed. V4334 Sgr should be observable in the mid and far-IR for many years to come and future monitoring seems worthwhile. It is also possible that the expanding shell will eventually thin enough to reveal the central star.

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